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Performance Impact of Coexistence Groups in a GAA-GAA Coexistence Scheme in the CBRS Band

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***Abstract*—The General Authorized Access (GAA) users in the Citizens Broadband Radio Service (CBRS) band are the lowest priority users. They must make sure that they do not cause harmful interference to the higher tier users while cooperating with each other to minimize potential interference among themselves. Thus, efficient GAA coexistence scheme is essential for the operation of GAA users and to obtain high spectrum utilization. Towards this goal, the Wireless Innovation Forum (WInnForum) has recommended three schemes to facilitate GAA-GAA coexistence. We had reported a performance study of one of these schemes (called Approach 1), but that study did not have any Coexistence Group (CxG). A CxG is responsible for managing interference among its CBRS devices (CBSDs). In this paper, we study the performance of Approach 1 without CxGs as well as with different number of CxGs, in various configurations. We conduct our study around two locations in the USA using actual terrain and land cover data of the continental USA. We evaluate performance of the scheme at different deployment densities, using different propagation models at those two locations with different number of CxGs. We provide some interesting insights into the costs and benefits of having CxGs in the deployment.**

I. Introduction

The Federal Communications Commission (FCC) in the USA has published the rules for commercial use of the spectrum in the 3.5 GHz band known as Citizens Broadband Radio Service (CBRS) band on a sharing basis [1]. The CBRS band has a three tiered access model. Current incumbents will operate in the highest tier followed by the Priority Access License (PAL) users in the middle tier and the General Authorized Access (GAA) users in the lowest tier. The incumbents must be protected from harmful interference caused by tier-2 (PAL) and tier-3 (GAA) users. PAL users should be protected from interference from GAA users. However, a GAA user cannot expect interference protection from higher tier users as well as from other GAA users in the same tier. PAL and GAA users' access to the spectrum in this band is managed by Spectrum Access Systems (SASs). As per the rule 47 C.F.R. § 96.35 in [1], GAA users must cooperate with each other to minimize the potential interference and to increase spectrum utilization. In the first phase of deployment in the CBRS band, there will be no PAL users. Hence, only GAA users will share the spectrum with the incumbents. Thus, GAA-GAA coexistence is very criticial to the success of this band. The Wireless Innovation Forum (WInnForum), which is involved in developing standards for operation of systems in the CBRS band has published Technical Reports recommending different schemes to faciliate effective GAA-GAA coexistence that should minimize mutual interference and increase spectrum utlization. The WInnForum has recommended three different schemes for GAA-GAA coexistence in three different Technical Reports [2]–[4]. The stake holders in the WInnForum could not agree to one particular scheme. Hence, they had to accept three competing schemes. The WInnForum does not recommend any particular scheme for any particular configuration. In fact, a SAS vendor is free to choose any one of these schemes for implementation of GAA-GAA coexistence. Performance comparison among the schemes is needed to determine whether a particular scheme is more suitable for a particular deployment configuration or not. But before that, the first step is to study performance of each scheme. Hence, in this paper, we take up one of those schemes, named *Approach 1*, proposed in [2] and study its performance in different configurations. It is envisioned that operators will group their CBSDs into, what are called, Coexistence Groups (CxGs). The CxGs will be responsible for managing interference among their respective CBSDs. Hence, a SAS will only be responsible for allocating bandwidth to the CxGs. We reported a simulation study of Approach 1 in [5]. But the study did not consider deployment with CxGs. Hence, in this work we study the effect of having different number of CxGs in the deployment on the performance of GAA-GAA coexistence along with the effect of different propagation models and deployment densities.

The main contributions of this work are as follows.

- The WInnForum does not define any performance metric to evaluate its proposed schemes. We have proposed a few performance metrics, which will be useful for operators and SAS administrators to evaluate the schemes as well as to compare different schemes.
- The only other study of GAA-GAA coexistence scheme, Approach 1 was reported by us in [5]. But that study did not have CxGs in the deployment. This study includes different number of CxGs in the deployment topology. Consequently, this work should provide insight into the performance of the scheme (Approach 1) proposed in [2] in terms of various deployment parameters and propagation models without CxGs as well as with different

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number of CxGs, highlighting the impact of CxGs in GAA-GAA coexistence.
- We choose actual locations in the continental USA as deployment locations. Furthermore, we use the WInnForum reference implementation of propagation models [6], which uses actual terrain and land cover data of the continental USA. Hence, our simulation results should be close to what one would expect in practical implementations.
- In one of our experiments, we deviate from the WInnForum scheme and show how more bandwidth (compared to WInnForum scheme) can be allocated at the cost of higher interference. Results from this experiment suggest that a different scheme can be designed to provide more bandwidth to the CBSDs if they agree to tolerate higher interference up to a certain threshold. So, our results based on this experiment can be used to design an alternative scheme.

TABLE I: List of Acronyms

CBRS	Citizens Broadband Radio Service
PAL	Priority Access License
GAA	General Authorized Access
SAS	Spectrum Access System
CBSD	CBRS device
CxG	Coexistence Group
CIG	CBSD Interference Graph
EW	Edge Weight
ET	Edge Threshold
BW	Bandwitdh
IM	Interference Metric
VB	Virginia Beach
SD	San Diego
ITM	Irregular Terrain Model
ABQ	Allocated Bandwidth Quality
CAF	Channel Allocation Factor
AIPA	Average Interference Power per unit Area
AIPCCG	Average Interference Power per CBSD per Channel per Grid

II. Related Work

Coexistence issues in different wireless bands have been studied in the past. Coexistence challenges for heterogeneous cognitive networks in the TV white space have been discussed in [7]. In this study, coexistence between the secondary users and the incumbents as well as coexistence among the secondary users is discussed. Coexistence among secondary users which are heterogeneous in their air interface and MAC protocol is also considered. Coexistence of LTE-licensed assisted access (LTE-LAA) and WiFi in the 5 GHz band has been studied in [8]. Coexistence of LTE-LAA and WiFi in the TV white space has been proposed in [9], [10]. Some of the solutions proposed in the literature are to modify LTE MAC protocol to improve coexistence performance. The above coexistence scenarios are addressed with specific air interface or MAC protocol in mind. However, the GAA-GAA coexistence schemes in the CBRS band proposed by the WInnForum do not assume any particular air interface or MAC protocol. As mentioned earlier, the WInnForum has proposed three approaches to solve the GAA-GAA coexistence problem. Approach 1 [2] treats bandwidth as the only resource and hence, allocates bandwidth to the CBSDs such that interfering CBSDs are assigned different channels to the extent possible. It does not manipulate transmit power of the CBSDs for coexistence purpose. If the deployment is too dense and hence, assigning different channels to interfering CBSDs is not possible, then this scheme allows some CBSDs to be assigned the same channel even if they may interfere with each other. A performance study of Approach 1 without CxGs has been reported in [5]. Approach 2 [3] deals with bandwidth and transmit power together and treats them as two types of resources. In dense deployment scenarios, if there are not enough channels to allocate different channels to interfering CBSDs, then less transmit power is allocated to a pair of interfering CBSDs so that intereference between them is mitigated and hence, can be allocated the same channel. Approach 3 [4] tries to maximize the amount of bandwidth allocated to individual CxGs by using a recursive algorithm to a cluster of CBSDs. It first identifies the CBSDs that are only connected directly to (i.e., interfere with) the CBSDs belonging to the same CxG as themselves. These CBSDs are refered to as *cluster of size 1*. These clusters can be allocated $100\,\%$ of the available bandwidth. To identify cluster of size 2, CxGs are chosen in pairs. For a given pair of CxGs, CBSDs belonging to one of the CxGs which have direct edges to CBSD belonging to the other CxG are marked as belonging to cluster of size 2. In this case, $50\,\%$ of available bandwidth is allocated to CBSDs belonging to one CxG and the other $50\,\%$ is allocated to CBSDs belonging to the other CxG. This algorithm is then applied recursively until all CBSDs are covered. A study of impact of propagation models on GAA-GAA coexistence and deployment density is presented in [11].

III. Overview of WInnForum Scheme (Approach 1)

The WInnForum has proposed three different schemes as solutions to GAA-GAA coexistence. In this section, we present salient parts of one of these schemes, named Approach 1 [2], which we have used in our study.

A. CBSD Interference Graph

For the purpose of GAA-GAA coexistence, a CBSD Interference Graph (CIG) is constructed in a deployment area. The vertices in the CIG are the CBSDs. An edge is placed between two CBSDs if either one or both of the CBSDs experience interference from the other CBSD above a given threshold. An edge weight (EW) between a pair of CBSDs is computed to determine if an edge should exist between the pair. If the computed EW is above a set Edge Threshold (ET), then an edge is established between the two CBSDs.

1) Edge Weight Calculation: For Edge Weight (EW) calculation, an Interference Metric (IM) between two CBSDs is first computed. IM is a measure of mutual interference between two CBSDs. Depending on the deployment scenario, IM may be computed in *area coordination* or in *point coordination* mode. For example, when CBSDs are deployed as LTE e-NodeB, then it needs to have a coverage area which should be protected from interference. Hence, in this case, IM in area coordination mode should be computed. On the other hand, when two CBSDs are deployed for fixed wireless service, one CBSD is deployed as the Base Transceiver Station (BTS) and the other is deployed as a Customer Premise Equipment (CPE) CBSD. They communicate in point-to-point mode and hence, interference at those CBSDs needs to be limited. The point coordination mode is appropriate in this case. In this study, we are interested in CBSD deployment for LTE coverage and hence, focus on area coordination mode.

In area coordination mode, for a pair of CBSDs, say CBSD-1 and CBSD-2, coverage area of each CBSD is computed. Coverage area of a CBSD, for a given transmit power, is the area around the CBSD such that the received signal strength at any point inside the area is above a set threshold. The WInnForum scheme specifies that this threshold should not be less than -96 dBm/10 MHz. The fraction of coverage area of CBSD-1 that overlaps with the coverage area of CBSD-2 is taken as CBSD-1's interference metric IM_1. Similarly, interference metric IM_2 of CBSD-2 is the overlap area expressed as a fraction of its coverage area. Then the EW between CBSD-1 and CBSD-2 is the maximum of IM_1 and IM_2. Note that EW takes a value between 0 to 1. For a given edge threshold (ET), an edge is established between CBSD-1 and CBSD-2 only if the EW is greater than the ET. This procedure is followed for every pair of CBSDs to obtain the CBSD interference graph.

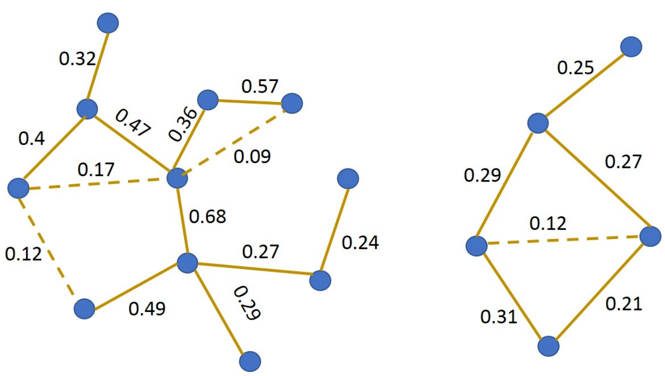

Fig. 1: An Example CBSD deployment with Edge Weights.

2) Connected Set: Once the CBSD interference graph is constructed, the next step is to generate *connected set(s)* off of it. A CBSD interference graph may contain one or more connected sets. Any two CBSDs in a connected set are connected directly through an edge or indirectly through other CBSDs in the interference graph. No CBSD within a connected set is connected directly or indirectly to any CBSD outside of the connected set [2].

Fig. 1 shows an example of CBSD Interference Graph when the ET is set to 0.2. In the figure, there is a solid edge between two CBSDs if their coverage areas overlap and the EW between them is greater than or equal to the ET. A dashed edge indicates

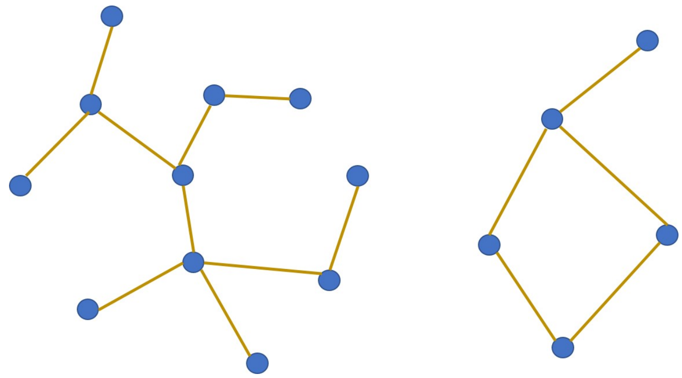

Fig. 2: Example CBSD Interference Graph when ET=0.2.

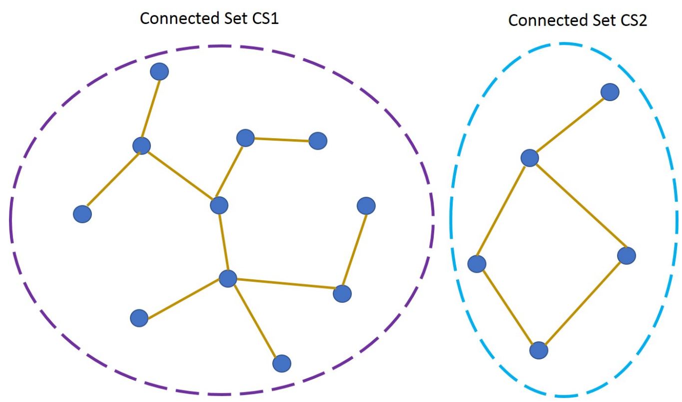

Fig. 3: Example Connected Sets.

that the coverage areas of the two CBSDs overlap, but the EW is less than the ET. No edge between two CBSDs implies that the coverage areas of the two CBSDs do not overlap. After applying edge threshold and removing the dashed edges, we get the CBSD interference graph as shown in Fig. 2. When the conditions of connected set are applied to this interference graph, we get two connected sets CS1 and CS2 as shown in Fig. 3.

3) Coexistence Groups: It is envisioned that operators in this band will create Coexistence Groups (CxGs) to faciliate GAA-GAA coexistence. A CxG consists of a group of CBSDs which will coordinate their own interference within the group. Thus, a SAS is only responsible for the allocation of bandwidth at the CxG level. The operator (or a CxG manager) of a CxG will take the bandwidth allocated to it and assign it to individual CBSDs within the CxG as per its interference management policy. As a result, a connected set will consist of one or more CxGs, i.e., CxGs are subgraphs in a connected set. The CBSDs which do not belong to any CxG are grouped together to form a common CxG (sort of a virtual CxG).

4) Graph Coloring of Connected Sets: The WInnForum scheme proposes a graph coloring approach [12] to allocate GAA bandwidth. The graph coloring starts at the CxG sub graph level. Graph coloring of a CxG involves computing its *chromatic number*. Chromatic number of a CxG is the minimum number of colors required to color the nodes of the

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CxG such that no two nodes having an edge between them are assigned the same color. Once chromatic number of each CxG inside a connected set is computed, then the *total chromatic number* of the connected set is computed by summing up the chromatic numbers of the CxGs belonging to the connected set. The bandwidth allocation to the CxGs is done as per the following procedure [2].

Let B be the total bandwidth available for the GAA users. Let C_i be the chromatic number of CxG_i. If there are M CxGs in the connected set, then the total chromatic number of the connected set is $C = \sum_{i=1}^{M} C_i$ and the bandwidth allocated to CxG_i is given by

$$BW_i = B \cdot \frac{C_i}{C} \quad (1)$$

Note that the bandwidth allocated to a CBSD is B/C. It is understood that for useful operation, a CBSD should get at least 10 MHz bandwidth. Consequently, if $B/C < 10$ MHz then the ET needs to be increased. This eliminates some edges from the connected set and hence, brings down the value of C. Then the bandwidth allocation process is repeated again. This procedure is repeated until $B/C \geq 10$ MHz.

IV. Simulation Setup

A. Deployment Model

We consider a deployment area of $5\,km \times 5\,km$ in size around Virginia Beach (VB) in the east coast (the center at latitude $36.872\,227$ and longitude $-76.023\,389$) and around San Diego (SD) in the west coast (the center at latitude $32.723\,588$ and longitude $-117.145\,319$) of the USA. We chose these two cities because the terrain around these cities are quite different. The terrain around Virginia Beach is somewhat flat, whereas it is hilly around San Diego. Propagation loss is a function of the terrain profile between transmitter and receiver. Hence, the two chosen cities have quite different propagation characteristics. The coverage areas of CBSDs are clipped by the above square deployment area. The deployment area is discretized by dividing it into grids of size $50\,m \times 50\,m$. CBSDs are uniformly placed within this deployment area as per the deployment density used for a given experiment. The parameters of the CBSDs used in our experiments are shown in Table II. These parameters are taken from [13]. All the CBSDs are assumed to have omnidirectional antennae.

In this study, since the FCC rule allows up to 70 MHz (out of total of 150 MHz) for PAL users, we assume that the rest 80 MHz is available for GAA users. We have used -96 dBm/ 10 MHz as the receive power threshold to compute the coverage area of a CBSD.

B. Deployment Configuration

In terms of CBSD deployment, we used a mix of Category A (CatA) and Category B (CatB) CBSDs as per Table III, which was derived from the data used in [13]. CatA CBSDs are low power devices and are typically deployed indoors, whereas CatB CBSDs are high power devices and are installed outdoors. We ran experiments with different deployment densities and propagation models at the two chosen locations (SD and VB). All the CatA CBSDs in our experiments are considered indoors, whereas all the CatB CBSDs are deployed outdoors. Note that, we do not have access to location and layout of buildings in VB and SD. So, the indoor CatA CBSDs are simply placed randomly in the deployment area. While calculating propagation loss for indoor CatA CBSDs, 15 dB is added as building loss.

TABLE II: CBSD Parameters

Area Type	Antenna Height [m] (Above Ground Level)		EIRP [dBm/10MHz]	
	Cat A	Cat B	Cat A	Cat B
Dense Urban	50 %: 3 to 15 25 %: 18 to 30 25 %: 33 to 60	6 to 30	26	40 to 47
Urban	50 %: 3 50 %: 6 to 18	6 to 30	26	40 to 47
Suburban	70 %: 3 30 %: 6 to 12	6 to 100	26	47
Rural	80 %: 3 20 %: 6	6 to 100	26	47

TABLE III: Ratio of CBSD Categories Deployed in Different Areas

Area Type	Cat A	Cat B
Dense Urban	90 %	10 %
Urban	90 %	10 %
Suburban	90 %	10 %
Rural	95 %	5 %

C. Creation of CxGs

At both SD and VB, we have run our experiments with different number of CxGs. If we need to have a total of N CxGs, we first create $(N-1)$ CxGs. A CBSD is uniform randomly placed into one of the $(N-1)$ CxGs or marked as a singleton CBSDs. After all the CBSDs are done with the placement, all the singleton CBSDs are grouped together and put into a newly created CxG.

D. Propagation Models

We have evaluated performance of the GAA-GAA coexistence scheme using two different propagation models: the Irregular Terrain Model (ITM) (in point to point mode) [14] and

TABLE IV: ITM Parameters

Parameter	**Value**
Polarization	1 (Vertical)
Dielectric constant	25 (good ground)
Conductivity (S/m)	0.02 (good ground)
Mode of Variability (MDVAR)	13 (broadcast point-to-point)
Surface Refractivity (N-units)	ITU-R P.452
Radio Climate	ITU-R P.617
Confidence/Reliability Var. (%)	50/50

the Hybrid model as described in the Requirement R2-SGN-04 in [15]. The ITM model, also known as the Longley-Rice model, is a propagation model based on electromagnetic theory, terrain features and radio measurements. The parameters used in the ITM propagation model are taken from requirement R2-SGN-17 in [15] and are listed in Table IV. The Hybrid propagation model is a model proposed by the WInnForum and is a hybrid between the ITM and the extended Hata (eHata) model. The eHata model [16] is an extension of the Hata model [17], which is essentially an empirical model based on a series of land-mobile measurements made by Okumura [18] over varied terrain. While the eHata model accounts for clutter loss, the ITM model does not consider clutter loss. Thus, in urban and suburban locations, where there is significant clutter loss, eHata loss would be higher than ITM loss. The Hybrid propagation model primarily sets its loss equal to the larger of the ITM loss and the eHata loss in urban and suburban area. In the rural area, the propagation loss using the Hybrid model is equal to the loss using the ITM model. Thus, in general, propagation loss using the Hybrid model is higher than or equal to the ITM model.

E. Performance Metrics

The WInnForum does not suggest any performance metrics for evaluating the GAA-GAA coexistence scheme. In this section, we describe the performance metrics used in our evaluations.

- *Average Interference Power per unit Area (AIPA)*: This metric captures the average interference experienced by a receiver on a given channel while it is inside the coverage area of a CBSD. If there are N_g grids inside the coverage area of a CBSD and I_i is the interference power (in dBm) received at the grid i over a channel c assigned to the CBSD, then the AIPA (in dBm) of the CBSD, on that channel is given by

$$AIPA^c = 10\log_{10}\left(\frac{\sum_{i=1}^{N_g} 10^{I_i/10}}{N_g}\right) \quad (2)$$

  Note that interference power on a channel at a grid inside the coverage area of a CBSD is the received power at that grid from all other CBSDs operating on that channel.
- *Allocated Bandwidth Quality (ABQ)*: This metric captures the average interference power (in dBm) per 10 MHz (or one channel) allocated to a CBSD per unit grid area of coverage of that CBSD. Let N_g^c be the number of grids inside the coverage area of a CBSD on channel c, and I_i^c be the interference power (in dBm) received at grid i over channel c. Let N be the number of channels allocated to the CBSD. Then the ABQ for that CBSD is given by

$$ABQ = 10\log_{10}\left(\frac{\sum_{c=1}^{N}\left[\frac{\sum_{i=1}^{N_g^c} 10^{I_i^c/10}}{N_g^c}\right]}{N}\right) \quad (3)$$

- *Average Interference Power per CBSD per Channel per grid (AIPCCG)*: The AIPCCG is defined as the average interference power (in dBm) per CBSD per channel per grid. For a given channel and a grid, maximum received power on that channel at that grid (from some CBSD) is considered desired signal and all other received signals are considered interference. Let I_i^j be the interference power (in dBm) received at a grid i on channel j. Let N_g, N_c and N_d be the number of grids, number of channels and number of CBSDs in the deployment area respectively. Then AIPCCG is given by

$$AIPCCG = 10\log_{10}\left(\frac{\sum_{j=1}^{N_c}\sum_{i=1}^{N_g} 10^{I_i^j/10}}{N_g \cdot N_c \cdot N_d}\right) \quad (4)$$

- *Channel Allocation Factor (CAF)*: Channel Allocation Factor (CAF) of a given channel is the fraction (or percentage) of CBSDs which have been allocated that channel. We use the mean (over all channels) and standard deviation of CAF to compare performances in different configurations.

Note that we did not use the traditional performance metrics used in wireless networks, such as throughput or capacity. In our case, when multiple CxGs are used, typically each CxG belongs to a network operator. Hence, interference in the coverage area of a CBSD of a given CxG from other CxGs is a very important factor for the operator. Amount of BW allocated to a CBSD is also an important metric for an operator. However, BW by itself may be misleading unless the quality (in terms of amount of interference) of the allocated BW is also measured. Thus, most of our performance metrics are centered around interference. Our metrics indirectly impact the capacity of the network (or CxG), but we feel that a network operator would be more interested in the direct performance metrics proposed by us.

V. Performance Results

In this section, we analyze the performance of WInnForum GAA-GAA coexistence scheme (Approach 1) using the performance metrics defined in the previous section. The experiments were run for all combinations of locations (San Diego and Virginia Beach), propagation models (ITM and Hybrid), and deployment densities of 3, 10, 30 and 50 CBSDs per square kilometer and with different number of CxGs. In all the figures in this section, the legends take the form $density\_ < num >, < num\_cxg > CxGs$, where $< num >$ and $< num\_cxg >$ represent density of deployment and number of CxGs repectively. When $< num\_cxg >$ takes the value w/o, that means the configuration did not have any CxGs. For example, label *density_3, 5 CxGs* repesents result from an experiment with deployment density of 3 CBSDs per km^2 with 5 CxGs.

A. Bandwidth Allocation

We first analyze the BW allocation in San Diego. Fig. 4 and Fig. 5 show the histogram of BW allocation for different deployment densities when using ITM and Hybrid propagation models respectively. For both ITM and Hybrid models, at high

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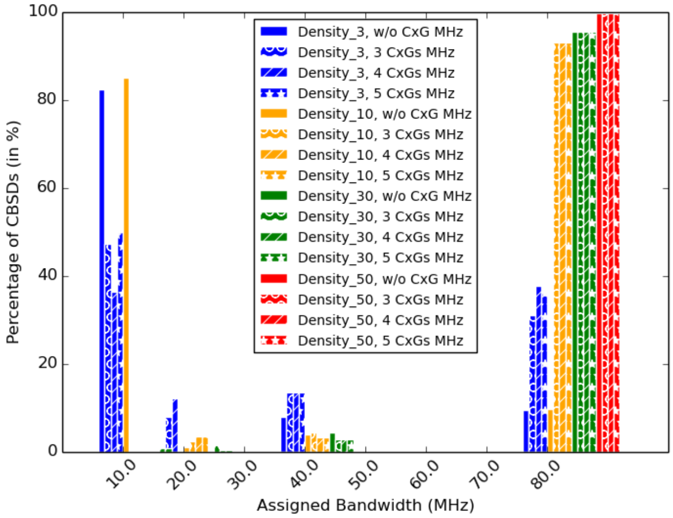

Fig. 4: Histogram of BW Allocation using ITM model (SD).

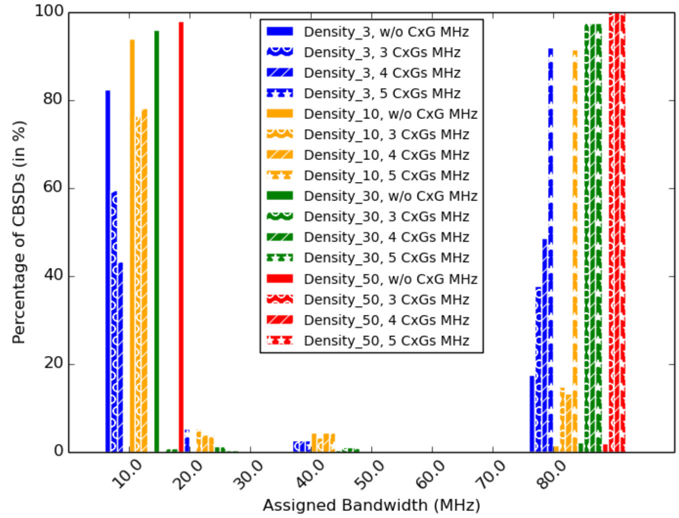

Fig. 5: Histogram of BW Allocation using Hybrid model (SD).

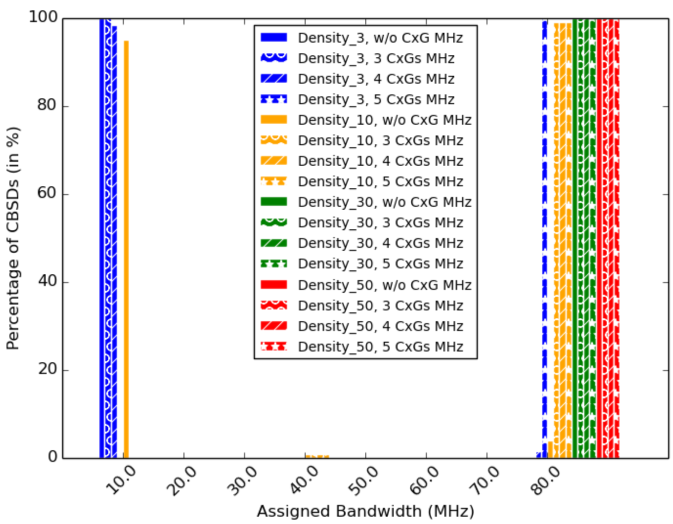

Fig. 6: Histogram of BW Allocation using ITM model (VB).

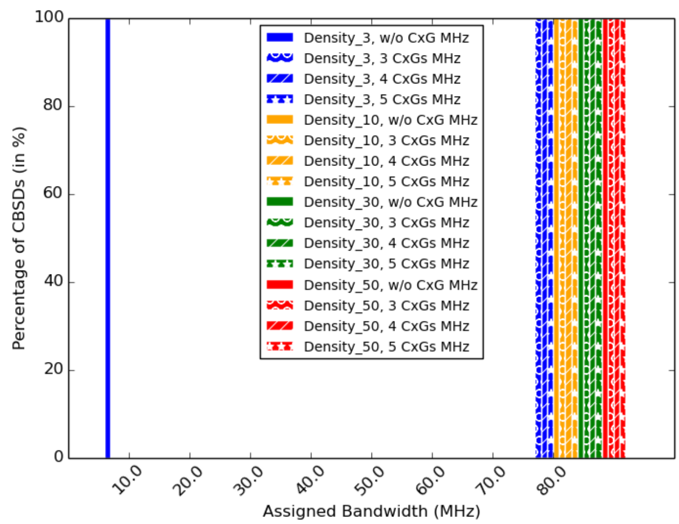

Fig. 7: Histogram of BW Allocation using Hybrid model (VB).

density (e.g., 30 and 50), having CxGs leads to more BW allocation (mass skews towards 80 MHz). At high density, the number of CxGs does not have much effect on BW allocation. At high density, the CIG is densely connected. Hence, ET is set to a high value to remove many edges and to make the CIG sparsely connected, so that the chromatic number comes down and almost maximum BW is allocated to most of the CBSDs. So, increasing the number of CxGs in a sparsely connected CIG does not have much impact on BW allocation. At low density (e.g., 3 and 10), with the ITM model, BW allocation is better (more mass to higher BW) when there are CxGs. For density 10, when the number of CxGs is changed, the BW distribution does not change much. For density 3, although BW distribution is different for different number of CxGs, it does not follow any trend. For the Hybrid model, at low density, there is no trend when the number of CxGs increases. BW allocation is a discontinuous function of chromatic number and ET. Sometimes, when the number of CxGs increases, the increase in chromatic number may be small enough that at least 10 MHz BW is allocated without increasing ET. So, in this case, BW allocation decreases. In some other case, the increase in the chromatic number will be large enough that minimum 10 MHz BW cannot be allocated to each CBSD. In this case, ET is increased to lower the chromatic number, which may lead to higher BW allocation. Hence, when the number of CxGs increases, the BW allocation may not follow any trend. Note that better BW allocation at high density and with CxGs comes at the cost of incurring more interference, as will be clear from AIPA performance. Comparing the results of the ITM model with the Hybrid model, we notice that with the ITM model, the mass is more skewed towards 80 MHz. However, for Hybrid model, there is some mass at different multiples of 10 MHz. This is because the Hybrid model incurs more loss (due to clutter) and hence the CIG is not as densely connected as it is when the ITM model is used.

At Virginia Beach (Fig. 6 and Fig. 7), like we observed in SD, for both the ITM and the Hybrid models, at high density (e.g., 30 and 50), having CxGs gets more BW (mass skews towards 80 MHz). In fact, for the Hybrid model, at high density, $100\,\%$ of CBSDs are allocated the entire available BW regardless of the number of CXGs or no CxG. VB has mostly flat terrain. Hence, the propagation loss is low (for both ITM and Hybrid). Therefore, at high density of deployment, the CIG is already highly connected leading to high chromatic number. Hence, ET is raised until each CBSD becomes a singleton CBSD and gets the entire 80 MHz BW. Note that the high BW allocation is achieved at the cost of incurring higher interference. At low density (e.g., 3 and 10), when the Hybrid model is used, all the CBSDs are allocated the entire BW when there are CxGs. Only for density 3, when there are no CxGs, the chromatic number is small enough to be able to allocate 10 MHz to each CBSD. When the ITM model is used at low density of deployment, some mass of the BW distribution appears at 10 and 40 MHz. At low density, the chromatic number is low enough to be able to allocate small BW without increasing ET to a high value. Comparing the BW allocation using the ITM and the Hybrid model, we notice that at high density there is not much difference between the BW performance. Since VB is has vastly rural land, the ITM and Hybrid loss do not differ from each other that much. However, at low density the difference between the ITM and Hybrid model loss accounts for the difference in BW distribution.

Notice that many BW values have no mass, because BW assigned to a CBSD is given by B/C (subject to a multiple of 10 MHz) as explained in Section III-A4. CIG of a deployment may not yield certain chromatic numbers (C) for a CS to have non zero mass at certain BW values. For example, in Figure 6, no CS has chromatic number 4 and hence the histogram has zero mass for 20 MHz BW.

It is difficult to compare BW allocation between SD and VB. In general, the way WInnForum Approach 1 BW allocation is designed, it is hard to determine which configuration will result in better BW allocation. Some configuration may produce higher BW allocation, but interference in those allocated channels will typically be higher. So, a better performance metric to compare different configurations is ABQ which is presented later.

B. Performance in terms of AIPA

Fig. 8 and Fig. 9 show the Cumulative Distribution Function (CDF) of AIPA of the channel with worst interference at different deployment densities with different number of CxGs in SD when the ITM and Hybrid propagation models are used respectively. The corresponding figures for VB are Fig. 10 and Fig. 11. For a given propagation model, as the deployment density increases, the AIPA becomes worse (i.e., higher interference) for both SD and VB locations. This is quite intuitive. When the deployment density increases, there is more interference due to transmission from higher number of CBSDs. Another factor that contributes to the AIPA increase is the increase in the ET at higher densities to be able to allocate a minimum 10 MHz BW to the CBSDs.

Now let us look at AIPA performance in SD. At high density (e.g., 30 and 50), for both the ITM and the Hybrid models, the number of CxGs has no effect on AIPA, i.e., AIPA performance remains the same as the number of CxGs increases. At low densities (e.g., 3 and 10), AIPA is worse when there are CxGs than when there are no CxGs. Having CxGs increases the chromatic number and hence sometimes ET has to be raised to bring the chromatic number down and be able to allocate at least 10 MHz BW. But the increase in ET results in more interference, i.e., higher AIPA. At low density, no particular trend is observed when the number of CxGs increases (for both the propagation models). Comparing the median performance between the Hybrid and ITM model, we notice that the Hybrid model gives better performance than the ITM model. This is because SD has large urban and suburban areas where Hybrid loss is more than ITM because the Hybrid model accounts for clutter loss. Hence, for any given configuration, AIPA is better with the Hybrid model than with the ITM model.

At VB, when the Hybrid model is used, an increase in the number of CxGs has no effect on AIPA, regardless of density of deployment. At high density, even without CxG, the chromatic number is high, so to get at least 10 MHz BW, ET is increased to a very high value to eliminate some edges in the CSs and bring the chromatic number down. Since the ET is already high without CxGs, when the number of CxGs is increased, it has no effect on BW allocation (see Figure 7) nor on the AIPA. But at low density of 3, having CxGs makes AIPA worse. When the ITM model is used at high density (e.g., 30 and 50), an increase in the number of CxGs has no effect on AIPA (due to same reason as mentioned in the case of Hybrid model), but at low density, AIPA performance is different with different number of CxGs. At low density, the CSs are sparsely connected. So, when the number of CxGs increases, the chromatic number increases to a point where ET needs to be increased to get rid of some edges and bring the chromatic number down (so as to get the minimum 10 MHz BW). Thus, the AIPA performance changes when the number of CxGs increases. Comparing median performance between the Hybrid and ITM model, we notice that the ITM model gives better performance than the Hybrid model in all configurations. This is the opposite of what we observed in SD. When the Hybrid

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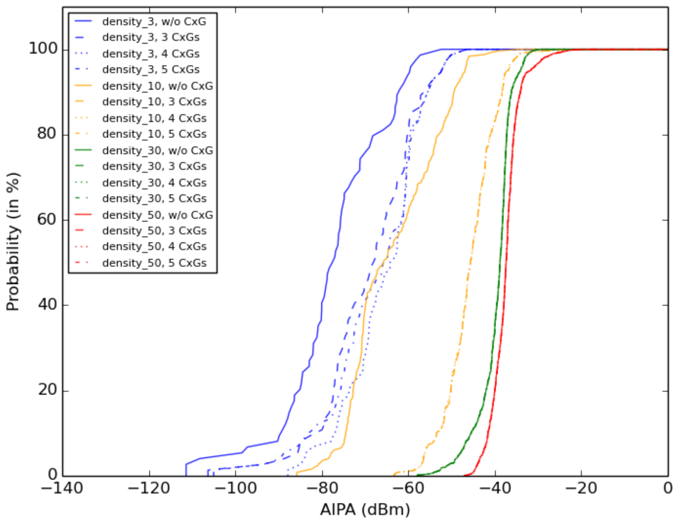

Fig. 8: CDF of AIPA with ITM propagation Model (SD).

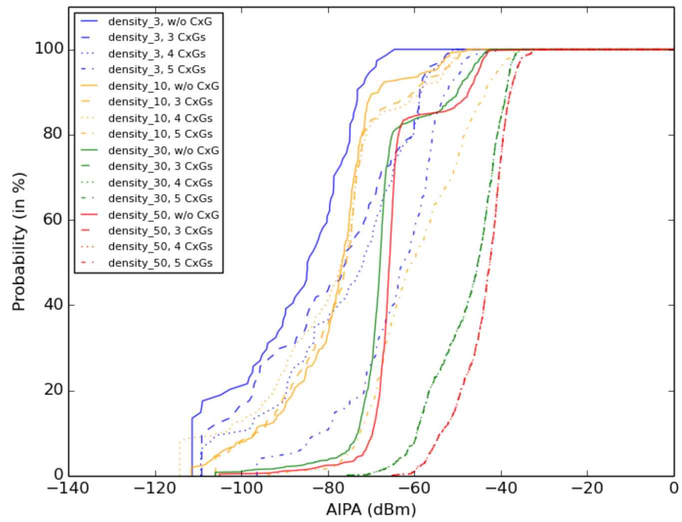

Fig. 9: CDF of AIPA with Hybrid propagation Model (SD).

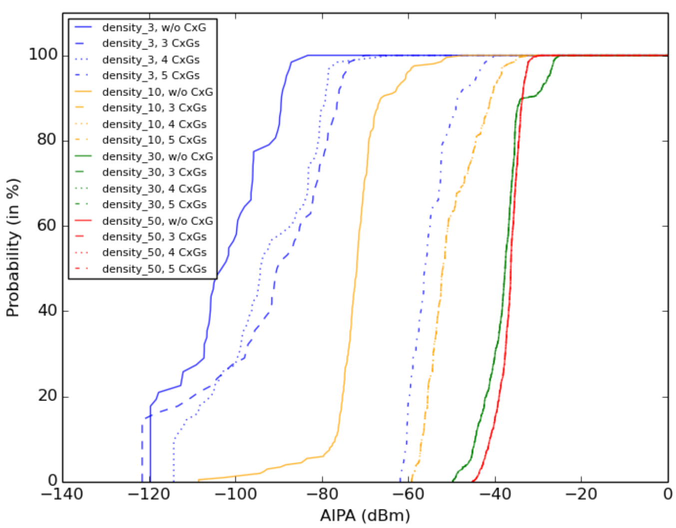

Fig. 10: CDF of AIPA with ITM propagation Model (VB).

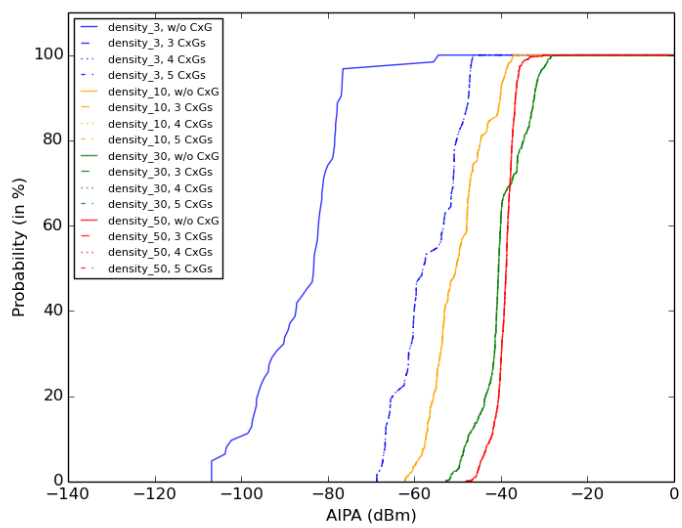

Fig. 11: CDF of AIPA with Hybrid propagation Model (VB).

model is used in urban and suburban areas, the propagation loss takes on the value provided by the eHata (since its loss is generally more than the ITM in such areas because eHata accounts for clutter loss), whereas in rural areas the propagation loss is equal to that provided by the ITM (as per Requirement R2-SGN-04 in [15]). In SD, the majority of grids are in urban or suburban areas, hence the propagation loss is determined by the eHata model in most cases when the Hybrid model is used, which leads to higher loss. Thus, the AIPA in SD is better with the Hybrid model than when the ITM model is used. In contrast VB has a large rural area. Thus, when the Hybrid model is used, the propagation loss in VB is mostly equal to that calculated by the ITM model. As a result, one would expect the AIPA performance of the ITM and the Hybrid model to be very close to each other in VB. However, as per the implementation of the Hybrid model by the WinnForum (see R2-SGN-04 in [15] and [6]), antenna height of a CBSD cannot be less than 20 m. Due to this requirement, for a CBSD having height less than 20 m, typically its coverage using the ITM model would be smaller than that using the Hybrid model. Smaller coverage area leads to less interference. Since VB is dominated by rural grids, the ITM model provides better AIPA performance than the Hybrid model.

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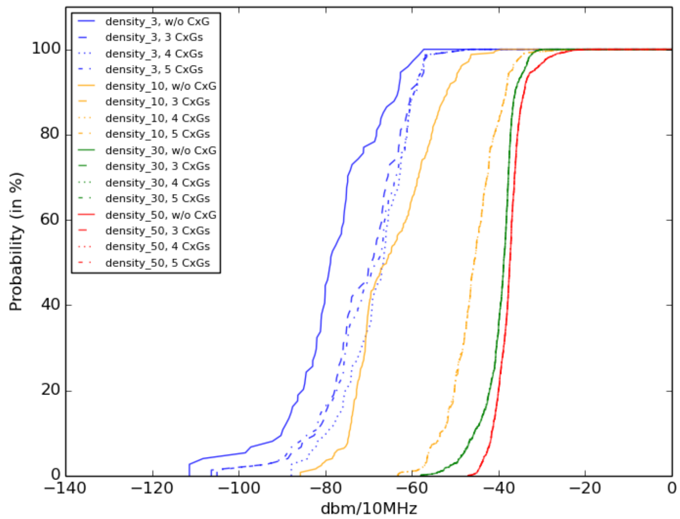

Fig. 12: CDF of ABQ with ITM propagation Model (SD).

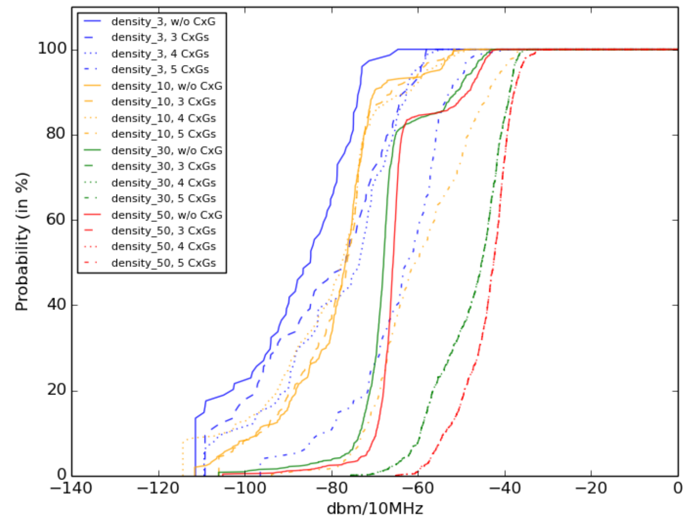

Fig. 13: CDF of ABQ with Hybrid propagation Model (SD).

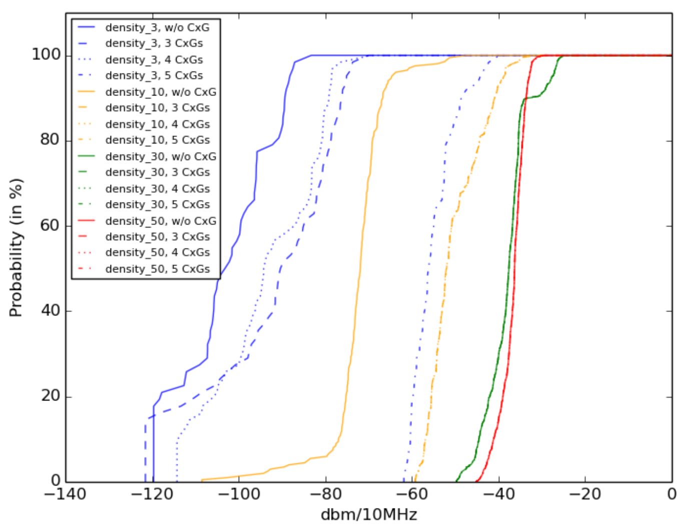

Fig. 14: CDF of ABQ with ITM propagation Model (VB).

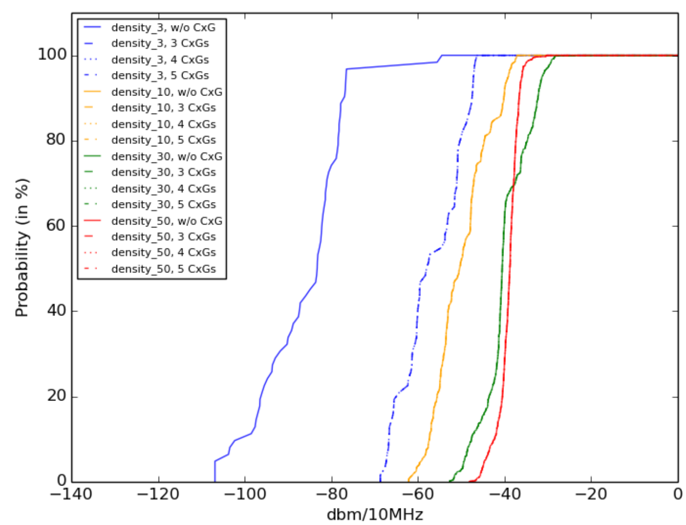

Fig. 15: CDF of ABQ with Hybrid propagation Model (VB).

C. Performance in terms of ABQ

Fig. 12 and Fig. 13 show the CDF of the ABQ at different deployment densities with different number of CxGs in SD when the ITM and Hybrid propagation models are used respectively. The corresponding figures for VB are Fig. 14 and Fig. 15. As expected, ABQ worsens as density increases for both locations and for both propagation models. At high densities, increasing the number of CxGs has no effect on ABQ at both the locations and for both the propagation models. The reason is same as explained in case of AIPA performance.

In SD, for both the propagation models, at low deployment density, having CxGs leads to higher median ABQ compared to no CxG case. This is because, having CxGs increases the chromatic number to the point where ET needs to be increased to be able to allocate at least 10 MHz BW. This results in increase in ABQ. When the number of CxGs is increased at low deployment density, it cannot be said that the median ABQ also increases. This is an artifact of the BW allocation algorithm used. The median ABQ performance of the Hybrid model is better (in most cases) than the ITM model. The reason is the same as that mentioned in AIPA performance: SD has large urban and suburban areas where Hybrid loss is more than ITM because the Hybrid model accounts for clutter loss. Hence, for any given configuration, median ABQ is better with the Hybrid model than with the ITM model.

In VB, the median performance when there are CxGs is worse than when there is no CxGs for both the propagation models. At low deployment density, having different number of CxGs does change the ABQ, but there is no trend. Median performance using the ITM model is better than when the Hybrid model is used. The difference is more at low deployment density. This is opposite of what we observed in SD. The reason is same as was explained in the case of AIPA performance.

D. Performance of BW Allocation vs AIPCCG

For this performance measurement, we deviate from the scheme proposed by the WInnForum. In this experiment, we want to observe the effect of allocating more BW at the cost of higher interference when we go beyond the ET at which the proposed WInnForum scheme would stop. Note that the proposed WInnForum scheme stops increasing the ET of a connected set once each CBSD in the connected set gets at least 10 MHz BW. Figures 16 and 17, show how increasing the ET results in more average BW allocation per CBSD at the cost of higher interference when the ITM and Hybrid models are used respectively in SD. Figures 18 and 19 are the corresponding figures for VB. Note that in this experiment, the CBSDs are allocated actual BW computed for a given ET, i.e., the final BW allocation is not rounded down to multiples of 10 MHz. Also note that in these figures, the scales of X-axis are not the same. The points marked as ETWF (ET WInnForum) represents the operating point of the WInnForum scheme in terms of average BW and AIPCCG. Note that, in general, there will not be a single ET value at this operating point since there could be multiple connected sets each with its own ET. Hence, we do not provide an ET value at this operating point in the graphs. For a given deployment density, we then continue to increase the ET beyond the corresponding ETWF. The interference metric in this experiment is AIPCCG and its computation is explained in Section IV-E.

In both SD and VB, as expected, when more BW is allocated to the CBSDs, the AIPCCG also goes up for all combinations of propagation models and deployment densities and number of CxGs. Also, as the deployment density increases, to get the same BW allocation, the ET needs to be higher (to bring the chromatic number down) and hence the corresponding AIPCCG is also higher. For a given propagation model and a given deployment density, as the ET increases (for densities for which there is room to increase ET), the CBSDs get more BW at the cost of higher AIPCCG. The performance Without CxG is almost always equal to or better than the case when there are CxGs. Like ABQ, at high deployment density, increasing the number of CxGs has no effect on AIPCCG performance.

In SD, the Hybrid propagation model produces better result than the ITM model for all deployment densities and for different number of CxGs, i.e., for a given allocated BW and a given configuration, the AIPCCG is lower for the Hybrid model than the ITM model. But in VB, the ITM model produces better BW allocation than the Hybrid model, i.e., for a given BW and a given configuration, AIPCCG for ITM model is lower than that of the Hybrid model. This reversal of performance between the two propagation models at the two locations is due to the same reason as explained in the AIPA performance. Comparing Hybrid propagation model based result between SD and VB, performance in SD is much better than in VB, especially at high density of deployment. This is due to the hilly terrain around SD which contributes to higher losses compared to VB which has more flat terrain. When ITM model is used, higher BW is allocated in SD at the cost of higher AIPCCG compared to VB, but at high deployment density performances in SD and VB are almost the same.

E. Performance in terms of CAF

Figure 20 and Figure 21 show the mean CAF in SD when the ITM and Hybrid propagation models are used respectively. The corresponding figures for VB are Figure 22 and Figure 23. We observe that mean CAF with CxGs is equal to or higher than the case when there is no CxG in all the four graphs. When there are CxGs, typically the ET is set to a higher value (than no CxG case) so that minimum 10 MHz can be allocated to the CBSDs. This leads to sparse connectivity in interference graph and hence allocation of more BW (or channels) to CBSDs due to decrease in chromatic number. Especially in high density scenarios, ET is raised close to or equal to 1.0 to get minimum 10 MHz for each CBSD. This makes almost every CBSD a singleton CBSD, which therefore is allocated all the channels. Thus, at high density (e.g., 30 and 50) we see the mean CAF value is close to $100\,\%$ when there are CxGs, at both the locations and for both the propagation models. At low density of 3, CAF stays much below $100\,\%$ at both the locations and for both the propagation models. This is because, at low density the ET remains relatively low, CIG is relatively sparsely connected. Hence, the chromatic number is not too high to warrant raising ET nor is it too low to allocate large BW. But the chromatic number is such that only one or two channels are allocated to a CBSD. When there is no CxG, in SD, even at high density the mean CAF is low when Hybrid propagation model is used. Because SD has mostly urban and suburban area and hilly terrain, Hybrid propagation loss is high. Thus, the interference graph becomes sparse when there is no CxG. Hence, the ET is not raised to a high value to achieve minimum BW allocation of 10 MHz, leaving many CBSDs having edges between them. These CBSDs are allocated a fraction of the total available BW (based on the chromatic number). Therefore, the mean CAF remains low in this case. However, when there are CxGs, the ET is set to a high value to bring chromatic number down in order to be able to allocate at least 10 MHz of bandwidth. With a very high ET (e.g., close to 1.0 in high density deployments), many edges between CBSDs are removed. This results in assigning entire available BW to many CBSDs. Hence, when there are CxGs, the mean CAF is high for this case.

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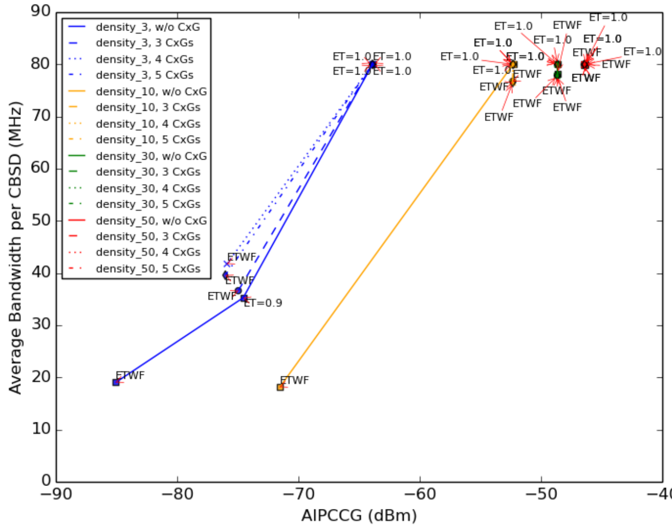

Fig. 16: BW vs AIPCCG at Different ET with ITM Model (SD).

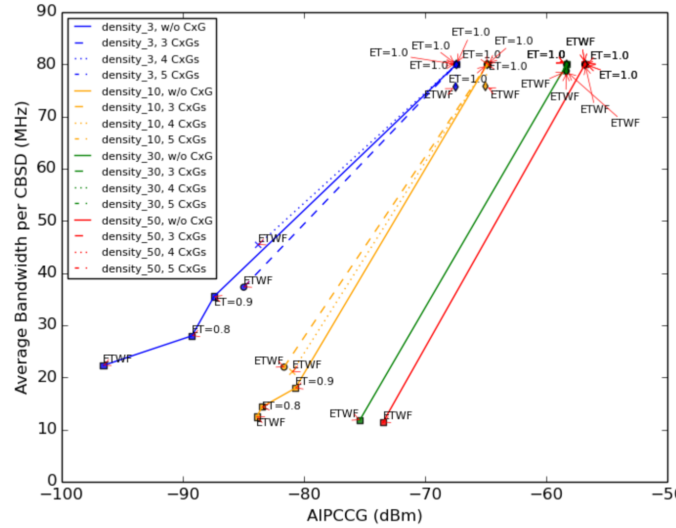

Fig. 17: BW vs AIPCCG at Different ET with Hybrid Model (SD).

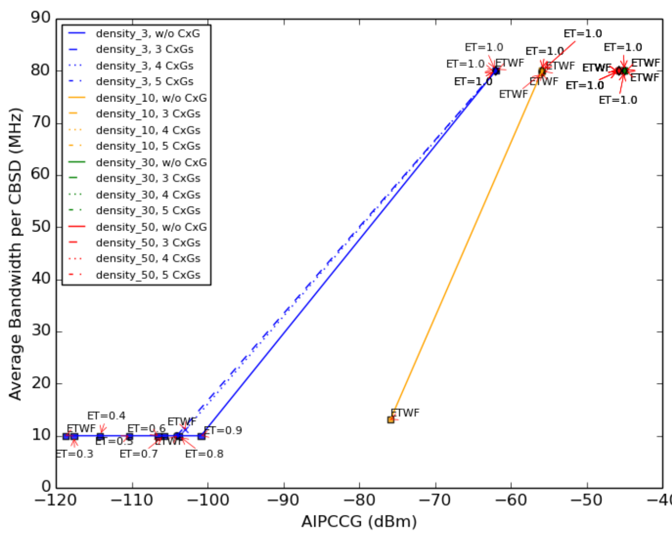

Fig. 18: BW vs AIPCCG at Different ET with ITM Model (VB).

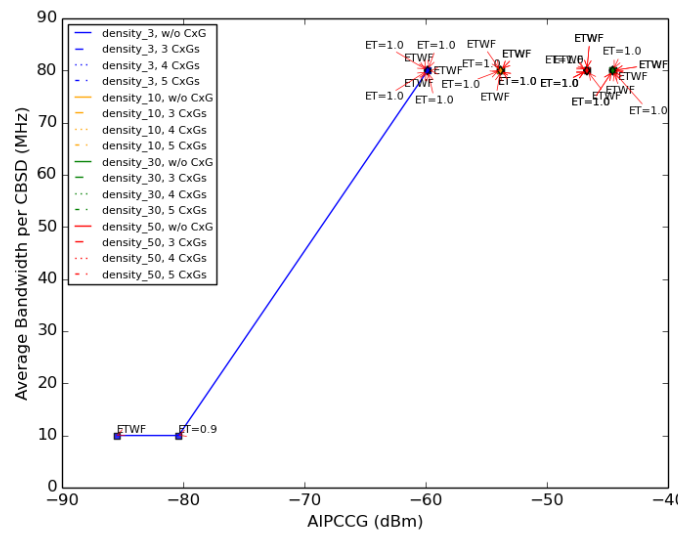

Fig. 19: BW vs AIPCCG at Different ET with Hybrid Model (VB).

Figure 24 and Figure 25 show the standard deviation of CAF in SD when the ITM and Hybrid propagation models are used respectively. The corresponding figures for VB are Figure 26 and Figure 27. Standard deviation of CAF is very low for all configurations having CxGs. But in most of the configurations, the standard deviation for no CxG case is high. This metric highlights the advantage of having CxGs. Having CxGs results in low standard deviation which implies that the channel (or BW) allocation is sort of balanced, i.e., each channel is assigned to almost equal number of CBSDs. This makes each channel of equal quality in terms of incumbent protection. In other words, almost equal number of CBSDs will be considered for evacuation of a channel regardless of which channel the incumbent appears on. Of course, the other advantage of having CxGs is the flexibility of allocating BW to individual CBSDs by the CxG manager. A SAS, in that case, is responsible for allocating BW at the CxG level and the CxG manager will then allocate BW to individual CBSDs based on its own interference policy.

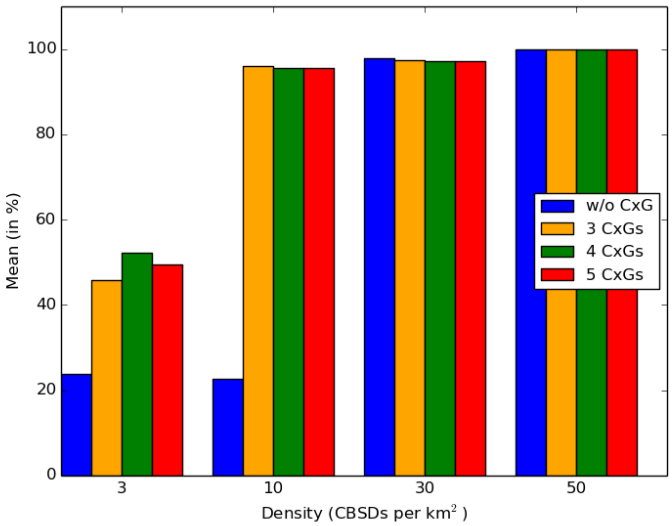

Fig. 20: Mean CAF using ITM Model (SD).

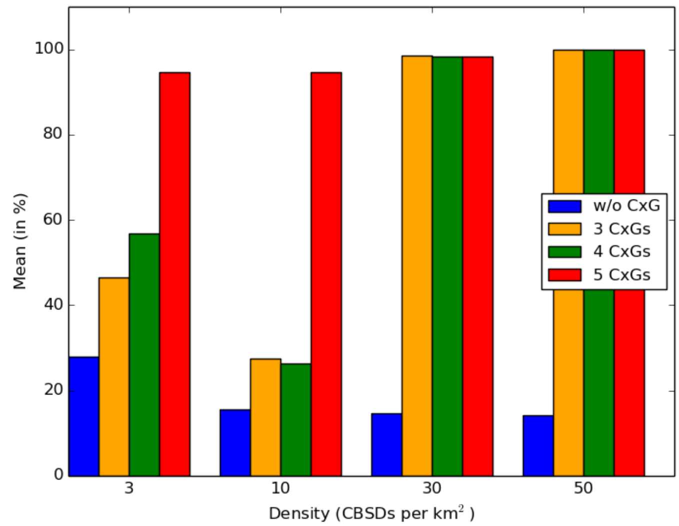

Fig. 21: Mean CAF using Hybrid Model (SD).

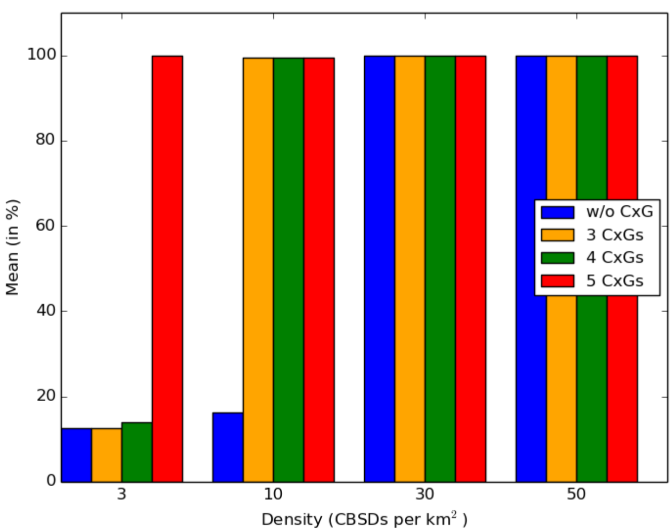

Fig. 22: Mean CAF using ITM Model (VB).

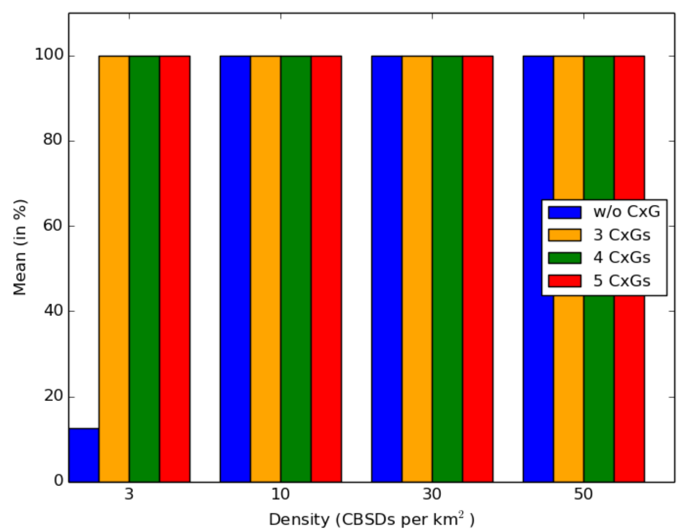

Fig. 23: Mean CAF using Hybrid Model (VB).

VI. Conclusion and Future Work

In this paper, we studied performance of the proposed WInnForum GAA-GAA coexistence scheme, called Approach 1, with deployment scenarios having no CxG and different number of CxGs. Our study looked at the effect of propagation model, deployment density and different number of CxGs on the performance of GAA-GAA coexistence. We found that the way WinnForum Approach 1 is designed, performance of the BW allocation is hard to predict when location, deployment density or propagation model is changed regardless of the number of CxGs. There are multiple system parameters at play while allocating BW (e.g., ET, number of CSs and chromatic number of each CS, number of CxGs), some of which are inter-dependent. Thus, BW allocation does not follow any particular trend. Performance in terms of AIPA, when there is no CxG is equal to or better than when there are CxGs in all the configurations. In SD, AIPA performance is better when the Hybrid model is used than when the ITM model is used. But in VB, it is the opposite, i.e., the ITM model gives better AIPA performance than the Hybrid model. ABQ performance without CxGs is always better than (or equal to) when there are CxGs for both the locations and both propagation models at all densities. ABQ at SD is better when the Hybrid model is used than when the ITM model is used, whereas at VB it is the opposite, in all CxG scenarios. In terms of AIPCCG also, configuration without CxG performs better than when

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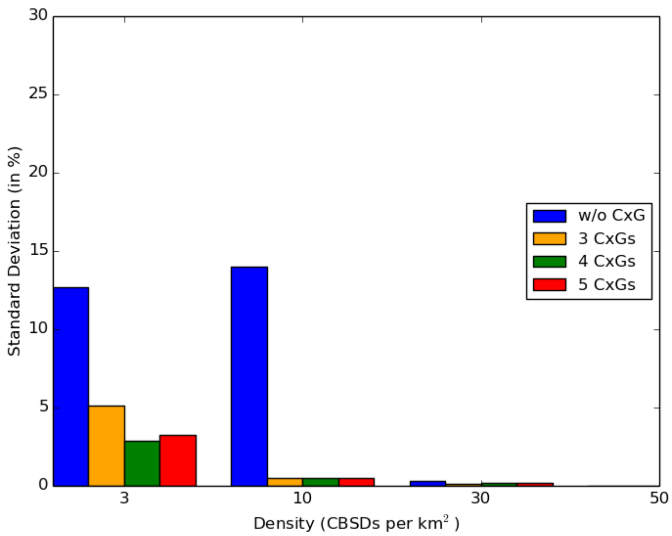

Fig. 24: Standard Deviation of CAF using ITM Model (SD).

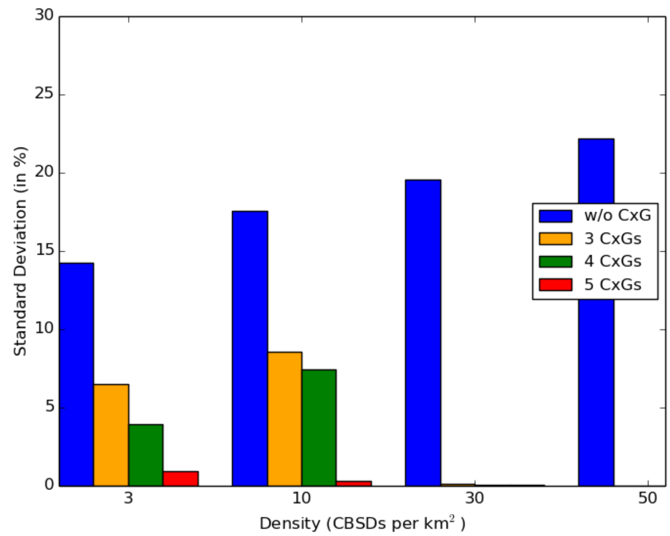

Fig. 25: Standard Deviation of CAF using Hybrid Model (SD).

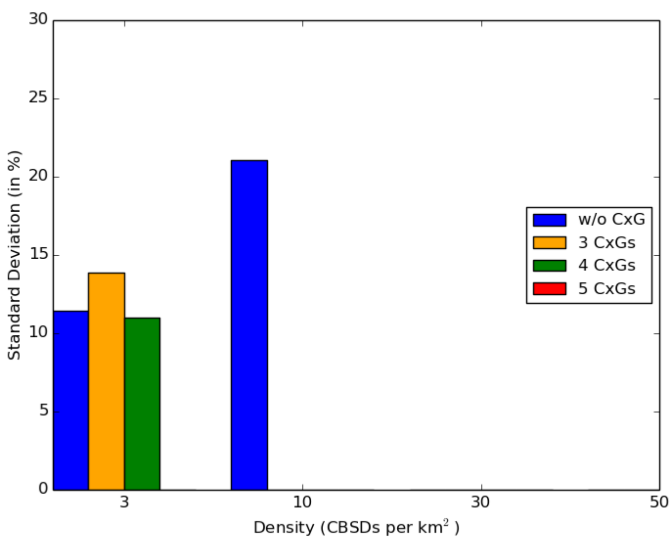

Fig. 26: Standard Deviation of CAF using ITM Model (VB).

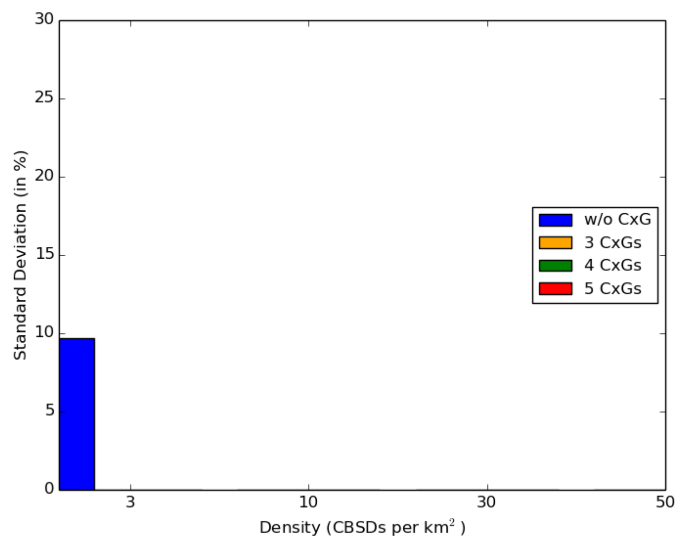

Fig. 27: Standard Deviation of CAF using Hybrid Model (VB).

CxGs are present at both the locations and for both propagation models at all densities. Again, in SD, AIPCCG performance using the Hybrid model is better than using the ITM model for all deployment densities and for different number of CxGs. But it is the opposite in VB, i.e., in VB, the ITM models gives better performance than the Hybrid model. Having CxGs in the deployment gives better performance in terms of CAF than when there is no CxG in all configurations. Mean CAF when there are CxGs is always equal to or higher than when there is no CxGs, whereas the standard deviation of CAF is lower when there are CxGs. This metric shows that not only do more CBSDs occupy a channel, but also each channel is assigned to almost equal number of CBSDs when there are CxGs. So, this makes each channel of equal quality in terms of incumbent protection. Of course, the other advantage of having CxGs is that a CxG manager has more flexibility when allocating BW to its CBSDs. When there is no CxG, the CBSDs are bound by the allocation determined by their respective SASes.

In terms of future work, from our experiment that studied the average BW vs AIPCCG (Section V-D), it is clear that an alternative scheme to allocate higher bandwidth at the cost of higher interference could be designed. The basic idea of this scheme is to set an upper limit on the amount of AIPCCG (interference). Based on the propagation model and density of deployment, the BW vs AIPCCG curve can be obtained. Then the amount of BW allocated to a CBSD corresponding to the upper bound of AIPCCG can be obtained from the curve. More detailed design and performance of such a scheme can be studied further and be compared with Approach 1. We are in the process of analyzing performance of the WInnForum's Approach 3 proposed in [4]. Once that work is done, comparison of performance between Approach 1 and Approach 3 can be carried out.

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